

Final Report

Task Research Title: Dusty Plasma Dynamics Near Surfaces in Space

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1. Introduction

The investigation “Dusty Plasma Dynamics Near Surfaces in Space” is an experimental and theoretical study of the dynamics of dust particles on airless bodies in the solar system in the presence of a photoelectron sheath generated by solar ultraviolet light impinging on the surface. Solar UV illumination of natural and manmade surfaces in space produces photoelectrons which form a plasma sheath near the surface. Dust particles on the surface acquire a charge and may be transported by electric fields in the photoelectron sheath generated by inhomogeneities in the surface or the illumination (such as shadows). The sheath itself has a finite vertical extent leading to (at least) an electric field normal to the illuminated surface. If dust particles are launched from the surface by some other process, such as meteoroid impact, or spacecraft activity on the surface, these grains become charged and move under the influence of gravity and the electric field. This can give rise to suspension of the particles above the surface, loss from the parent body entirely (if accelerated beyond escape velocity), and a different distribution of dust ejecta from what would be expected with purely gravitational dynamics.

2. Description of Research

We performed experiments to study the characteristics of photoelectron sheaths, the charging of dust grains in a sheath, and the levitation of grains in a plasma sheath.

We carried out an extensive suite of experiments on the photoelectric charging properties of a variety of dust grains. This has led to experimental confirmation of a simple (but previously untested) model for the charge collected on isolated grains.

A “double plasma” device was used to investigate the charging of dust grains in a photoelectron sheath. The device consists of two aluminum cylinders 30 cm in diameter and 30 cm long placed end to end. The interior of the chamber is covered in stainless steel to reduce photoemission and secondary electron emission from the walls. The chamber is pumped by a diffusion pump to a base pressure of 4×10^{-7} torr. The experiments are performed at one end of this device. Ultraviolet light is provided by a 1 kW Hg-Xe arc lamp. The light is collimated by a lens and directed through a quartz window into the apparatus. The optical components pass wavelengths down to 200 nm. The light impinges on an electrically isolated 12.5 cm diameter zirconium foil disc which acts as a photocathode. Zirconium was chosen for its low work function (4.05 eV).

Dust is introduced into the chamber by agitating a thin metal disk with a 0.5 mm diameter central hole. An o-ring, 1 cm in diameter, is glued to the center of the disk and contains the dust. The disk is agitated by an electromagnet controlled remotely by computer. Dust particles released into the chamber fall into an electrostatically shielded Faraday cup which provides a time history of the charge in the cup. Charge signals from dust grains falling into the cup can be positively identified by the characteristic shape of the waveform from the Faraday cup and the timing of the signal corresponding to the drop time of the dust particle through the chamber. We have studied the charging properties of elemental and composite materials: zinc, copper, graphite, glass, JSC-1

lunar soil simulant, and JSC-Mars-1 martian soil simulant. The latter two samples come from standard supplies prepared at the NASA Johnson Space Center.

We have measured the charge collected on these grains within a photoelectron sheath and the charge induced by photoemission from the grains in the absence of any photoelectron sheath or other ambient plasma. Data on grain charging are shown in figures 1-3.

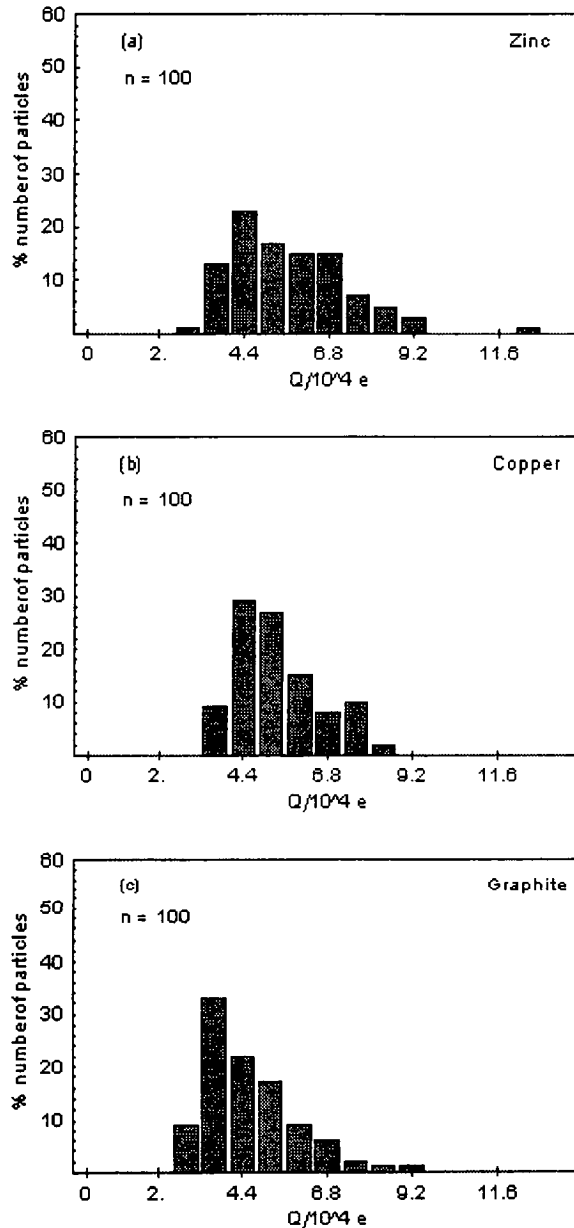


Figure 1: Charge distributions for 100 particles of zinc (a), copper (b), and graphite (c) dust dropped through the UV beam.

Figures 1 and 2 show data for elemental materials zinc, carbon, and graphite, while figure 3 shows data collected for glass spheres. When the elemental grains fall through a photoelectron sheath they acquire a net negative charge (Figure 2), and when

they fall through the UV beam in the absence of a sheath, photoemission leads to a loss of electrons and a net positive charge (Figure 1). The situation is more complicated for composite materials, such as glass, JSC-1, and JSC-Mars-1. For these materials we see that triboelectric charging (due to contact friction between particles) can overwhelm the charging due to the photoelectron sheath or photoemission (Figure 3). Figure 3a shows the distribution of charges on 100 glass particles in the absence of a UV light source. These charges are due to triboelectric charging. Figure 3c shows that when falling through the sheath, those particles which initially had a positive charge due to triboelectric charging have collected photoelectrons and neutralized so that no positively charged grains remain. Figure 3b shows a slight increase in positively charged grains due to photoemission from the triboelectrically charged glass particles.

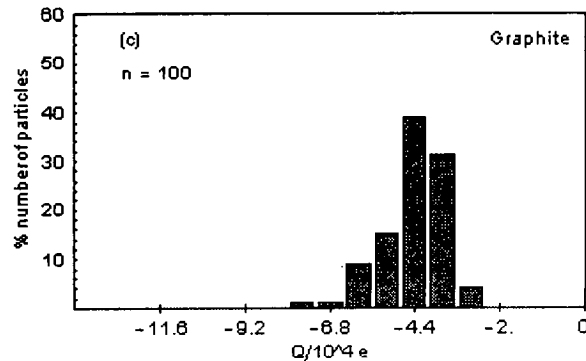
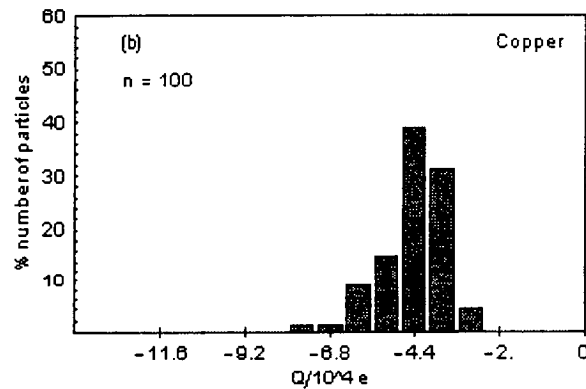
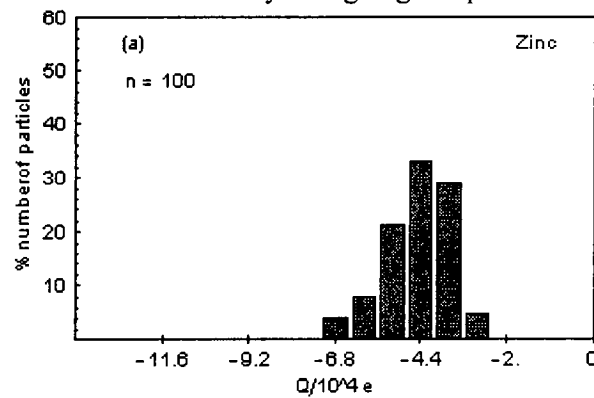


Figure 2: Charge distributions for 100 particles of zinc (a), copper (b), and graphite (c) dust dropped through the photoelectron sheath.

We have shown that our experimental results are consistent with a simple model of the capacitance of a photoelectrically isolated dust grain, $C = Q/V$, where Q is the charge on the particle and V is the particle potential with respect to the local plasma. The capacitance of a sphere of radius r is given by $C = 4\pi\epsilon_0 r$, and the potential is obtained from the maximum energy of the photons from our UV light source and the work function of the grains. The model fit to our data is shown in figure 4.

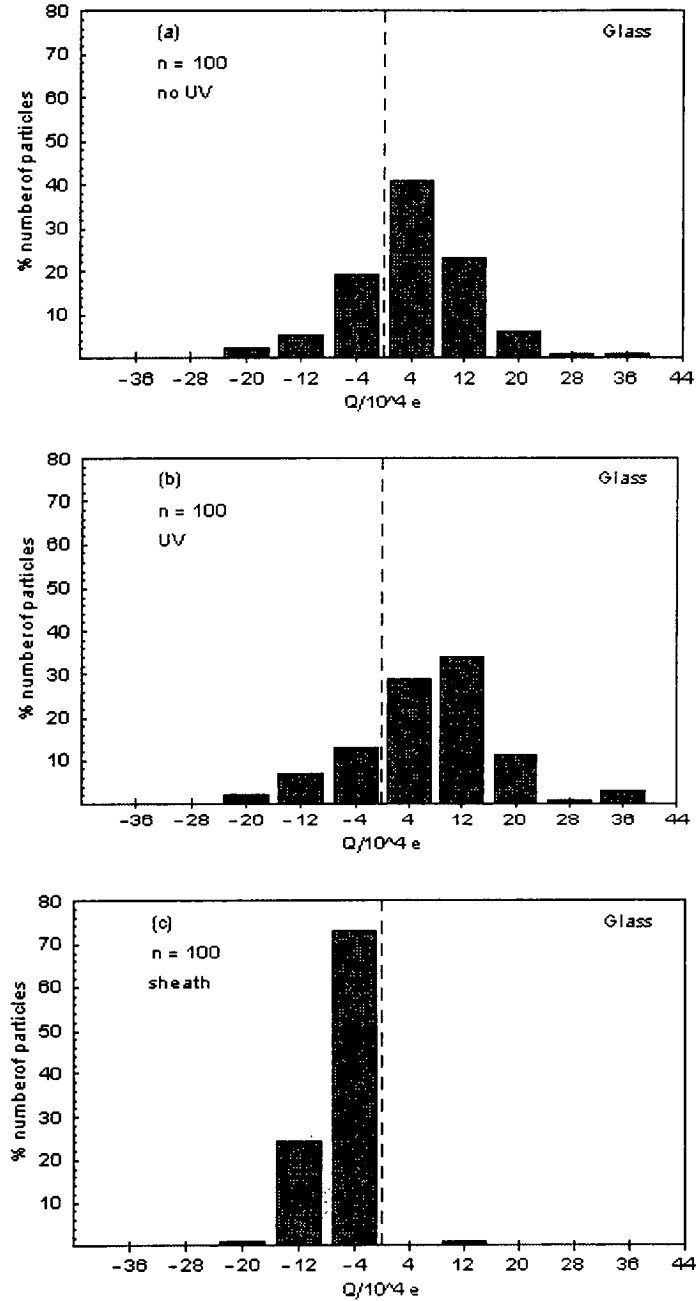


Figure 3: Charge distributions for 100 glass spheres dropped through the chamber with (a) no UV illumination; (b) UV illumination but no photoemitting plate, and (c) a photoelectron sheath generated by UV illumination of a photoemitting plate.

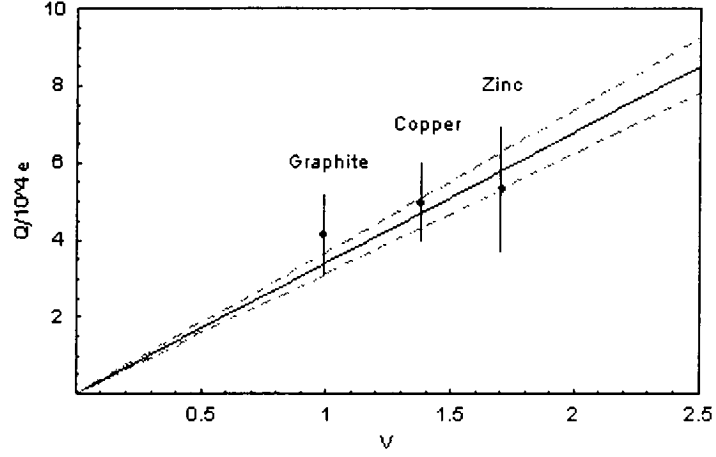


Figure 4: The measured charge due to photoemission on zinc, copper, and graphite given by the mean \pm the standard deviation for the best gaussian fits to the charge distributions. The potential, V , is given by the maximum photon energy minus the work function of the particle. The solid line is the capacitance of an isolated spherical grain for particles in the middle of our range of particles sizes, $r = 49\mu\text{m}$, and the dashed lines indicate the capacitance for the smallest ($r=45\mu\text{m}$) and largest ($r=53\mu\text{m}$) grains in our samples.

We have used the charge collected on the grains as a probe of the photoelectron layer and successfully measured the layer thickness (Figure 5).

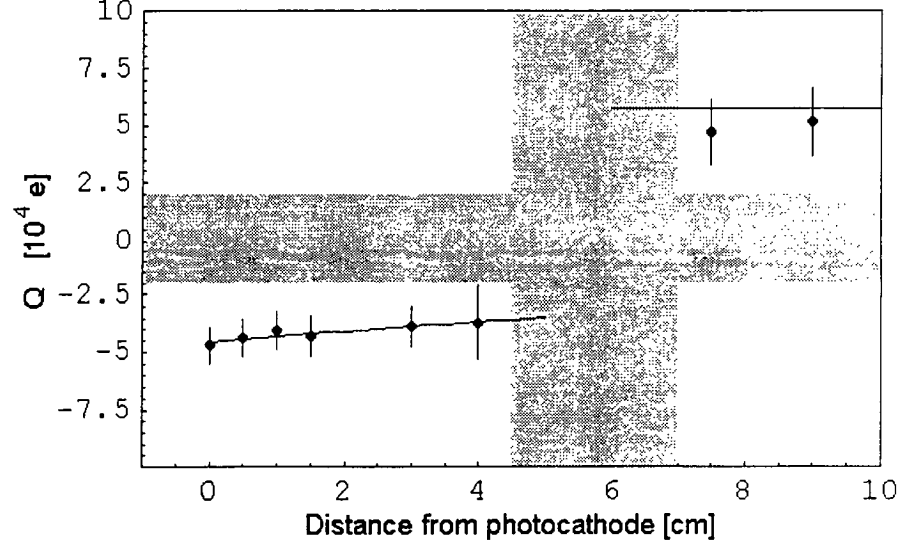


Figure 5: The charge measured on zinc particles having fallen through the sheath as a function of the distance from the photocathode. The horizontal shaded area indicates the detection threshold of $\pm 2 \times 10^4 e$. The continuous curve on the left indicates the expected theoretical charge using a Maxwellian sheath. The horizontal line on the right indicates the maximum charge on grains due to photoemission and is set by the work function of the zinc particles and the high-energy photon cutoff. Due to this cutoff, the sheath itself cannot extend to infinity and — as indicated from our charge measurements — the photoelectron density vanishes in the range of $\approx 4.5 - 7$ cm from the photocathode. This area is marked by the vertical shaded region.

Upon completion of the individual dust particle charging experiments, we constructed a new vacuum to simulate dusty surfaces in space. This new plasma device has a horizontal surface rather than the vertical surface used for the individual grain charging experiments. The chamber is evacuated to 5×10^{-7} torr by a turbomolecular pump. Dust particles rest on a ~ 12 " diameter aluminum plate. The plate can be electrically biased to aid dust levitation. An insulated hammer underneath the plate is controlled external to the chamber to agitate the dust, while an accelerometer attached to the plate provides a quantitative measurement of the acceleration on the surface. This initial step is a crude simulation of spacecraft activity on a planetary surface or disturbances produced by meteoroids and secondary impacts from meteoroid impact ejecta.

Plasma is produced by filling the chamber with argon gas from an inlet valve. The ionization sources are the same 1 kW Mercury-Xenon arc lamp used for the photoelectron dust charging experiments and/or a tungsten filament inside the chamber. There is a Langmuir probe inside the chamber to measure plasma characteristics. Plasmas have been generated inside this new chamber via photoemission from the arc lamp. For the purposes of getting levitated dust layers the stronger electric fields produced by a plasma sheath with the tungsten filament are used at this stage. A Faraday cup located beneath a small hole in the plate measures the charge on dust particles that fall from the plate. The circuitry is completed for each of these components, and they are operating successfully. For example, the Langmuir probe measures a background electron density of $\sim 6 \times 10^6 \text{ cm}^{-3}$ and a temperature of $\sim 4 \text{ eV}$ for a typical plasma with the filament as an ionization source (pressure of 1×10^{-4} torr; primary electrons accelerated by -40 V bias voltage between the filament and the wall of the chamber). This corresponds to a Debye length of roughly 0.6 cm .

In order to view dust particles on and above the plate, illumination is provided by an air-cooled argon laser. The laser passes through a cylindrical lens, which produces a flat laser plane in the chamber. The height of the laser plane can be adjusted to examine dust at various heights above the plate. A viewing window perpendicular to the incoming laser plane allows observation of the dust by a video camera. A narrowband filter ($488 \pm 2 \text{ nm}$) rests in front of the video camera. This causes the laser light reflected off dust particles to be seen as very bright while incident light from the filament or outside of the chamber is eliminated.

We successfully created stable layers of dust levitated above the surface in a plasma sheath. Particles were found to levitate above the surface even without mechanical agitation if there is a sufficient voltage bias on the surface. Levitated particles include polystyrene microspheres, glass microballoons, and JSC-1 lunar regolith simulant. Dust particles are observed to levitate singly or in clouds. Observations are made of single, levitated polystyrene grains (chosen for their well-defined mass). The dust potential and charge of a levitated grain calculated using OML theory agrees well with those deduced from balancing the forces in the sheath, given the measured levitation height. The levitation height as a function of surface bias, obtained by selecting the stable

intersection of the dust potential from OML theory with the dust potential from force balance, also agrees well with the measured height.

Particles exposed to a UV source consistently levitate at a slightly lower height than particles not exposed to UV. This is most likely due to photoemission from the particles, which causes the dust potential to be less negative. Exposure to UV may cause particles to drop out of the sheath and be deposited onto the surface. Particles are not always stationary within the sheath, they are observed to move both vertically and horizontally above the surface. Thus, UV exposure may result in dust falling out of the sheath in a different location than it entered. This is one mechanism by which dust can be transported across a surface.

These experiments support the model of electrostatic processes being the primary cause of dust levitation and transport near surfaces in space. Many different types of particles levitate under a variety of plasma environments. In addition, conditions that are even more conducive to dust levitation than those in the experiments are found throughout the solar system.



Figure 6: One video frame capture showing scattered light from glass microballoons levitated in a plasma sheath (bright spots in left half of image). The image is taken through a filter which makes the surface difficult to see.

We developed a numerical model of the transport of charged dust over planetary surfaces and applied it to the regolith of asteroids. We conducted simulations above surfaces with gravitational accelerations matching that of Mercury ($g=360 \text{ cm-s}^{-2}$) and a medium-sized asteroid ($g=1 \text{ cm-s}^{-2}$). Particles were launched at speeds between 1 and 10^3 cm/s . Particles tend to accumulate at topographic boundaries because their trajectories intersect crater or block walls (Figures 7-8).

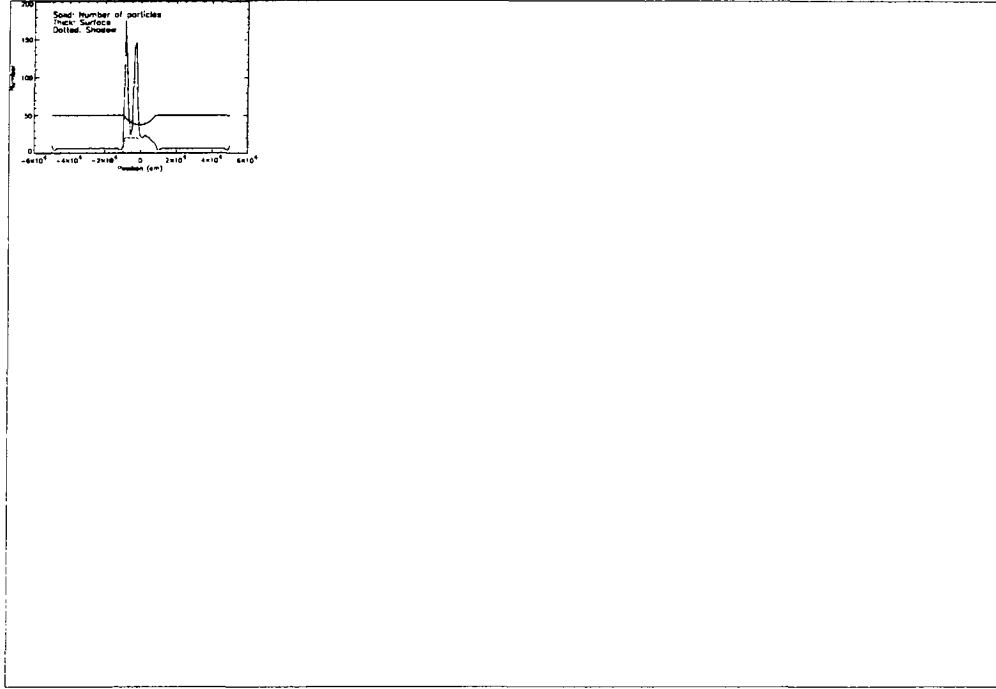


Figure 7: distribution of final dust positions for a simulation with a shallow crater (thick line) and sunlight incident from the left resulting in a shadow on the crater floor (dotted line). Particles suspended in the photoelectron sheath fall to the surface when they enter the shadow and the electric field vanishes, and also accumulate near the crater walls (solid line).

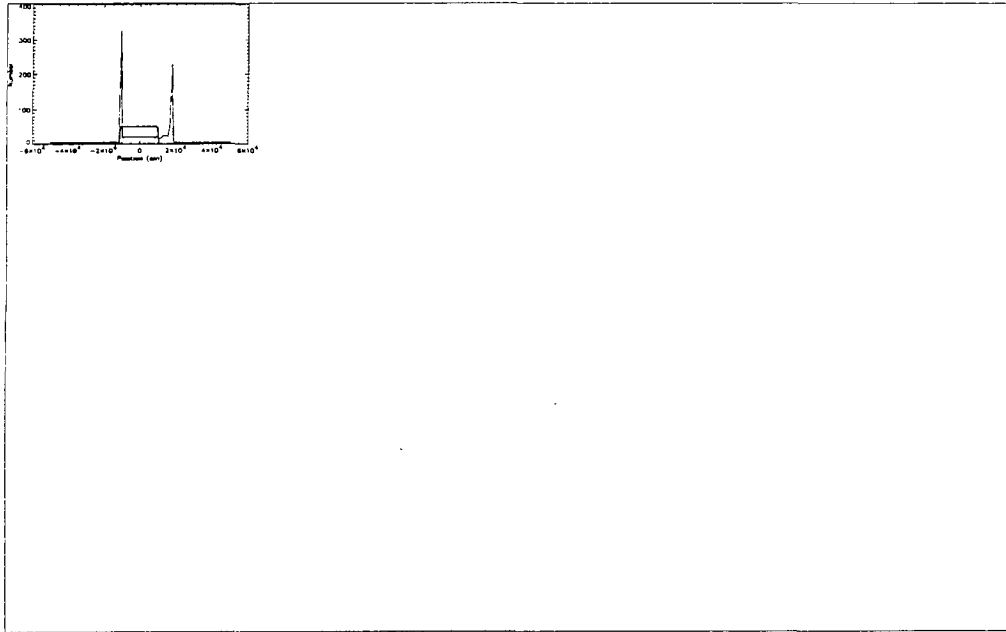


Figure 8: Distribution of dust positions like Figure 7, but for a surface with a rectangular block (thick line) instead of a crater. Sunlight is incident from the left, and the dotted line indicates the region of the block's shadow. Particles accumulate at the block boundary and at the shadow boundary (solid line).

Particles also accumulate at sheath boundaries where the electric force vanishes. Particles that are levitated in the sheath move across the surface with their initial horizontal velocity. This initial velocity could be the result of an impact on the surface, for example, or by levitation due to a large surface bias. When the particle crosses the local terminator, the photoelectron sheath vanishes and gravity is the only remaining force on the particle and it falls to the surface. The distribution of particle positions on the surface show this as large accumulations at the boundaries of shadows produced by topography (Figures 7-8). Future work will include a full three-dimensional model of the sheath above realistic surfaces with a time-variable terminator.

3. Publications and Reports.

Our results have been presented at the following meetings and in the following publications in the past year.

1. Colwell, J. E., M. Horányi, S. Robertson, and A. A. Sickafoose 2002. Levitation and Transport of Charged Dust over Surfaces in Space. In *Dusty Plasmas in the New Millenium* (R. Bharuthram, M. A. Helberg, P. K. Shukla, F. Verheest Eds., AIP Conference Proceedings 649), 438-441.
2. Sickafoose, A. A., J. E. Colwell, M. Horányi, and S. Robertson 2002. Experimental Dust Levitation in a Plasma Sheath near a Surface. In *Dusty Plasmas in the New Millenium* (R. Bharuthram, M. A. Helberg, P. K. Shukla, F. Verheest Eds., AIP Conference Proceedings 649), 235-238.
3. Sickafoose, A. A., J. E. Colwell, M. Horanyi, and S. Robertson 2002. Experimental Levitation of Dust Grains in a Plasma Sheath. *J. Geophys. Res.* (in press).
4. Sternovsky, Z., A.A. Sickafoose, J. E. Colwell, S. Robertson, and M. Horanyi 2002. Contact Charging of Lunar and Martian Dust Simulants. *J. Geophys. Res.* (in press).
5. Sickafoose, A. A., J. E. Colwell, M. Horányi, and S. Robertson 2001. Experimental Investigations on Photoelectric and Triboelectric Charging of Dust. *J. Geophys. Res.*, **106**, 8343-8356.
6. Sickafoose, A. A., J. E. Colwell, M. Horanyi, and S. Robertson 2000. Photoelectric Charging of Dust Particles in Vacuum. *Phys. Rev. Lett.* **84**, 6034-6037.
7. Colwell, J. E., M. Horányi, A. Sickafoose, S. Robertson, R. Walch 1998. Dynamics of Dust in Photoelectron Layers Near Surfaces in Space, Fourth Microgravity Fluid Physics and Transport Phenomena Conference, NASA, Aug. 12-14, 1998, pp. 96-97.
8. Colwell, J. E., M. Horányi, S. Robertson, A. Sickafoose 2002. Levitation and transport of charged dust over surfaces in space. Int. Conf. on Phys. Of Dusty Plasmas, May 20-24, Durban, South Africa.

9. Colwell, J. E., M. Horányi, S. Robertson, A. Sickafoose 2002. Dynamics of Charged Dust Near Surfaces in Space. 6th Microgravity Fluid Physics and Transport Phenomena Conference, Aug. 14-16, Cleveland OH.
10. Sickafoose, A. A., J. Colwell, M. Horanyi, and S. Robertson 2002. Dust grain charging and levitation in a weakly collisional DC sheath. 44th Annual meeting of the Division of Plasma Physics of the American Physical Society, Orlando, Nov. 11-15, *Bull. Am. Phys. Soc.* **47**, 121.
11. Sickafoose, A.A., S. Robertson, J.E. Colwell, and M. Horanyi, Laboratory Measurements on the Photoelectric Charging of Dust, IAU Colloquium 181: Dust in the solar system and other planetary systems, Canterbury, UK, 10-14 April 2000.
12. Sickafoose, A.A., S. Robertson, J.E. Colwell, and M. Horanyi, Experimental Photoelectric Charging of Dust Particles, National Radio Science Meeting (URSI), Boulder, CO, 4-8 January 2000.
13. Robertson, S., A. Sickafoose, J. Colwell, and M. Horanyi, Dusty Plasma Dynamics Near Surfaces in Space, Abstracts of the Fifth Microgravity Fluid Physics & Transport Phenomena Conference, 97, 2000.
14. Sickafoose, A.A., J.E. Colwell, M. Horanyi, and S. Robertson, Experimental Studies on the Photoelectric Charging of Dust Particles, 8th Annual Workshop on the Physics of Dusty Plasmas, Santa Fe, NM, 25-28 April 2000.
15. Sickafoose, A., J. Colwell, M. Horanyi, and S. Robertson, Photoelectric Charging of Dust Particles, *Bull. Amer. Phys. Soc.* **44**(7), 49, 1999.
16. Sickafoose, A.A., S. Robertson, J.E. Colwell, and M. Horanyi, Photoelectric Charging of Dust in Space, *Bull. Amer. Astron. Soc.* **31**(4), 1170, 1999.
17. Sickafoose, A.A., J.E. Colwell, M. Horányi, and S. Robertson, Photoelectric and triboelectric charging of dust grains on planetary surfaces, *Bull. Amer. Astron. Soc.*, **32**(3), 1084, 2000. (Presented at the annual meeting of the Division of Planetary Sciences of the American Astronomical Society, Pasadena CA, October 2000)